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**HIGH RESOLUTION PLASMA DIAGNOSTICS FOR
HIGH POWER MICROWAVE (HPM) GENERATION RESEARCH**

Final Report

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HIGH RESOLUTION PLASMA DIAGNOSTICS FOR HIGH POWER MICROWAVE (HPM) GENERATION RESEARCH

I. Summary Statement of the Purpose and Significance of the DURIP Program

The goal of this program is to substantially enhance the spatial and temporal plasma diagnostic resolution capabilities in order to investigate plasma phenomena and pulse shortening in novel high power microwave (HPM) sources. We plan to purchase a laser spectroscopic system which will allow in situ measurements of strong electromagnetic fields. Noninvasive laser diagnostics are a highly valuable research tool, which can be applied to the understanding of HPM plasma phenomena in a variety of HPM sources. Several facilities, including the Phillips Laboratory, Hughes Research Laboratories, Titan, and SLAC have expressed strong interest in using this powerful diagnostic when available, in order to better understand pulse shortening effects in their HPM devices; we anticipate arranging to make the diagnostic available to the HPM community on a collaborative research basis. Also, HPM sources at the University of Maryland currently operate with electron beam duration around 0.1 μsec , and increasing the pulse duration to over 1 μsec is an obvious route to higher microwave energy per pulse. Field emission guns capable of $>1 \mu\text{sec}$ are very uncommon. We propose to have a long pulse, high current gun custom designed and fabricated. The combination of advanced laser diagnostics and a state-of-the-art field emission gun to be purchased under this instrumentation grant (DURIP) will enable detailed study and enhanced understanding of plasma effects and pulse shortening issues in HPM sources.

II. Summary of Achievements

As proposed, we purchased the following three diagnostics systems:

- 1) Dual pulsed dye laser system, streak & framing camera and associated accessories (gated intensified CCD camera, pulsed wavemeter, spectrometer, flash pumped dye laser, optics and beam transport).
- 2) Streak & framing camera and associated accessories (photomultipliers, dissectors, optical table, fast digitizers @ 1 GHz sampling rate).
- 3) Diagnostics and design of a long pulse (1 μsec) field emission electron gun with stable cross section for HPM sources.

A draft of a scientific publication describing the results of a microsecond, relativistic electron beam gun with stable cross section is attached in Appendix A.

APPENDIX A: Draft copy

RELATIVISTIC HIGH-CURRENT ELECTRON BEAM OF MICROSECOND PULSE DURATION WITH STABLE TRANSVERSE DIMENSIONS GENERATED BY A FIELD-EMISSION CATHODE

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Principles of a diode based on a cold-emission cathode are presented. A combination of the diode geometry and magnetic field lines profile prevents the cathode plasma radial movement and allows to generate high-current annular REBs with invariable cross section during microsecond time intervals.

Introduction.

High-current relativistic electron beams (REB) are usually generated by field-emission cathodes, also referred to as plasma cathodes or cold cathodes. The mechanism of electron beam generation is roughly the following. First, a strong electric field ($\sim 10^6 \div 10^7$ V/cm) promotes electron emission from cathode surface, heating it to a temperature of evaporation and further ionization of the gas (several eV). The typical duration of this process is $\sim 10^{-9}$ s, so at this initial stage the density of the created plasma is very high, almost that of a solid. Later on the plasma itself plays a role of electron emitter.

Electron current density that is possible to extract from a plasma cathode may be roughly estimated according to flux conservation law: $S_c \cdot n_p \cdot v_e = S_b \cdot n_b \cdot v_b$. Here S_c is the square of cathode emissive area, n_p is plasma density, v_e is the plasma electrons velocity, and the parameters with indices "b" at the right of the formula describe electron beam square section, electron density and velocity. Assuming $S_c \sim S_b$, $n_p \sim 10^{22}$ cm⁻³, $v_e \sim 10^7$ cm/s, and $v_b \approx c \approx 3 \cdot 10^{10}$ cm/s one may see that the beam electrons density $n_b \sim 10^{19}$ cm⁻³ and current density $J = e \cdot n_b \cdot v_b \sim 10^8$ A/cm² may be extremely high. Actually these values are several orders less ($n_p \sim 10^{16}$ cm⁻³ at a distance > 0.1 cm from the cathode [1]). Nevertheless, application of cold cathodes allows to produce REBs with much higher electron current densities ($\sim 10^4$ A/cm²) than with conventional thermoionic cathodes ($< 10^2$ A/cm²). Hereafter we discuss only diodes and REBs with azimuthal symmetry, although physical processes are the same for planar (sheet, ribbon) electron beams.

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Most applications, e.g., microwave oscillators, demand a REB to be generated and utilized in a strong magnetic field, about or more than 1 T. In such conditions cathode plasma propagates along magnetic field lines with the velocity $\sim 10^7$ cm/s, hence, in order to avoid a cathode-diaphragm shortcut for generation of REBs during microsecond time intervals magnetically insulated diodes [2] are applied: coaxial cathode and anode tube in a strong magnetic field.

In the course of accelerator voltage pulse plasma from the cathode propagates not only along magnetic field lines, but also expands across them, causing an increase of the electron beam radius. The velocity of this transverse plasma expansion is several millimeters per microsecond that may be crucial, e.g., for microwave devices of microsecond pulse duration, sensitive to electron beam geometry.

Application of a diaphragm in order to restrict the beam radius (useful with REB duration < 100 ns) is not a cure due to at least two reasons. First, if a circular REB that expands along the radius is «cut» from outside, its total current may change significantly in the course of the pulse. Second, under the action of the electron beam bombardment plasma appears on the diaphragm surface. This diaphragm plasma propagates toward the cathode, interacts with the beam electrons and modifies the REB parameters. As a consequence, the diaphragm causes a microwave pulse shortening in the relativistic BWO [3].

Electric current in a coaxial magnetically-insulated diode.

The value of the electric current of an annular REB generated in a coaxial magnetically-insulated diode (MID) was obtained in [4] and extended in [5] often referred to as the formula of Fedosov. For the origin of this formula often causes questions, here we briefly represent its derivation in a simplified form, trying to demonstrate the physical sense of the diode current value. Further we will consider infinitely strong magnetic field.

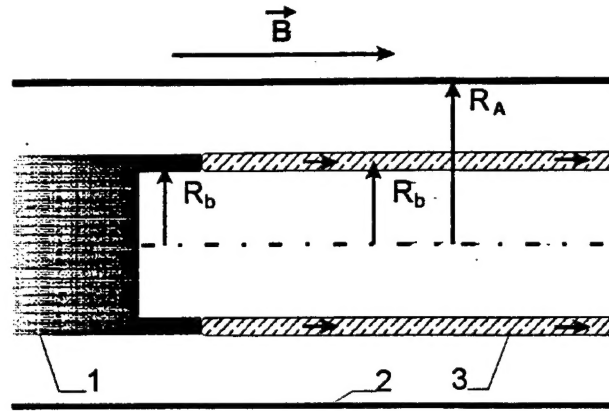


Fig. 1. Magnetically insulated diode. 1 — cathode, 2 — anode tube, 3 — electron beam.

A coaxial MID, see Fig. 1, consists of a cathode with the radius R_C and an anode with the radius R_A . An electron beam produced in a MID has an annular shape with the radius R_b equal to that of the cathode: $R_C = R_b$, the beam thickness is vanishing. The electron current I is a product of longitudinal charge density σ and the beam velocity v :

$$I = \sigma \cdot v \quad (1).$$

The beam potential Φ far right from the cathode is also determined by the charge density σ :

$$\Phi = \sigma \cdot 2 \ln \frac{R_A}{R_b} \quad (2).$$

Relativistic factor γ characterizes cathode voltage U : $\gamma = 1 + \frac{U}{\frac{mc^2}{e}} \approx 1 + \frac{U}{511 \text{ kV}}$, where m and e are an electron mass and charge respectively and c is light speed. Relativistic factor of the

beam electrons γ_b is determined by the beam velocity v : $\frac{v^2}{c^2} = 1 - \frac{1}{\gamma_b^2}$. On the other hand, γ_b

depends on the beam potential Φ :

$$\gamma = \gamma_b + \frac{\Phi}{\frac{mc^2}{e}} \quad (3)$$

It is easy to show (substituting σ into (1) from (2) and Φ from (3)) that the electron current I and the relativistic factor γ_b of the beam electrons in the drift tube are mutually related as:

$$I = \frac{mc^3}{e} \cdot \frac{1}{2 \cdot \ln \frac{R_A}{R_b}} \cdot \frac{(\gamma - \gamma_b) \cdot \sqrt{\gamma_b^2 - 1}}{\gamma_b} \quad (4).$$

Here $mc^3/e \approx 17$ kA. The function $I(\gamma_b)$ in Formula (4) has a maximum at $\gamma_b = \gamma^{1/3}$, this maximum is the vacuum limiting current I_{lim} :

$$I_{lim} = \frac{mc^3}{e} \cdot \frac{1}{2 \cdot \ln \frac{R_A}{R_b}} \cdot (\gamma^{2/3} - 1)^{3/2} \quad (5).$$

This vacuum limiting current I_{lim} is the maximum beam current able to propagate in a tube irrespectively to the fact where and how this beam had been generated. In case of electron beam generation in a MID the current value is determined by process at the cathode.

The admittance that the cathode emission ability is infinite (this corresponds to the case of an explosive cathode) and the total current is finite demands longitudinal electric field at the cathode edge to be equal to zero: $E_z = 0$. This means that electric field does not affect the cathode applying a force in longitudinal direction. In turn, the latter guarantees that the system "field+electrons" is enclosed over z-direction, i.e. pulse exchange takes place only between electrons and the field. In these circumstances, in [4] the pulse flux conservation law was used. We will try to interpret the process of electron acceleration as a result of electric field pressure.

Electromagnetic field energy density $(E^2 + B^2)/8\pi$ may be considered as the field pressure. An integral of this pressure over a transverse cross section forms a longitudinal force. The difference F of these forces in far left F_+ and far right F_- regions (in respect to the cathode edge) increase the amount of accelerated electrons in the diode, i.e. changes their total pulse p in the course of a certain time interval: $F = F_+ - F_- = \frac{dp}{dt}$.

Since electric current is continuous, the magnetic field does not vary along the axis, so it does not change the balance of forces and may be neglected. In both far left and far right regions electric field exists only at the radii between R_C and R_A . Moreover, the electric field in both these regions has no longitudinal component, it is pure radial.

The voltage between the cathode and the anode is U , hence, the electric field E_+ over radius r at the left from the cathode is:

$$E_+ = \frac{U}{r \cdot \ln \frac{R_A}{R_C}}, \quad R_C < r < R_A \quad (6).$$

The integral electric force acting from the left side may be expressed as:

$$F_+ = \int_{R_c}^{R_A} \frac{E_+^2}{8\pi} \cdot 2\pi r \cdot dr = \frac{U^2}{4 \ln \frac{R_A}{R_c}} = \left(\frac{mc^2}{e} \right)^2 \cdot \frac{1}{2 \ln \frac{R_A}{R_c}} \cdot \frac{(\gamma - 1)^2}{2} \quad (7)$$

At the right end the total electric field has the same profile:

$$E_- = \frac{\Phi}{r \cdot \ln \frac{R_A}{R_c}}, \quad R_c < r < R_A \quad (8)$$

and the force at the right side is as follows:

$$F_- = \int_{R_c}^{R_A} \frac{E_-^2}{8\pi} \cdot 2\pi r \cdot dr = \frac{\Phi^2}{4 \ln \frac{R_A}{R_c}} = \left(\frac{mc^2}{e} \right)^2 \cdot \frac{1}{2 \ln \frac{R_A}{R_c}} \cdot \frac{(\gamma - \gamma_b)^2}{2} \quad (9)$$

During time interval dt a certain number of electrons is accelerated, their total mass is equal to

$\sigma \frac{m}{e} \cdot v \cdot dt$. These electrons are accelerated from zero velocity, and total pulse increase is:

$$\frac{d}{dt} p = \frac{d}{dt} \left(\sigma \frac{m}{e} v dt \right) \cdot v \gamma_b = \sigma \frac{m}{e} c^2 \frac{\gamma_b^2 - 1}{\gamma_b} = \left(\frac{mc^2}{e} \right)^2 \cdot \frac{1}{2 \ln \frac{R_A}{R_b}} \cdot (\gamma - \gamma_b) \frac{\gamma_b^2 - 1}{\gamma_b} \quad (10)$$

Being multiplied by light velocity c the force balance becomes the pulse flux conservation law, used in [4].

Comparing (7), (9), (10) one may see that

$$\frac{(\gamma - 1)^2}{2} = \frac{(\gamma - \gamma_b)^2}{2} + (\gamma - \gamma_b) \frac{\gamma_b^2 - 1}{\gamma_b} \quad (11)$$

Besides obvious $\gamma_b = 1$, the only positive root of (11) is:

$$\gamma_b = \sqrt{\frac{1}{4} + 2\gamma} - \frac{1}{2} \quad (12)$$

Formula (12) determines the relativistic factor of an annular REB with negligible thickness generated in a MID in infinitely strong magnetic field. Being substituted into (4) it determines the electric current in the MID (Fedosov current).

For low relativistic case, $\gamma = 2 \div 4$, Fedosov current is about 3/4 of the vacuum limiting current I_{lim} , Formula (5), for a REB with the same geometry.

For non-relativistic case, $\gamma - 1 \ll 1$, Fedosov current corresponds to "the law of 3/2":

$$I = \frac{1}{3\sqrt{3}} \cdot \sqrt{\frac{e}{m}} \cdot \frac{U^{3/2}}{\ln \frac{R_A}{R_C}}$$

The beam potential Φ of Fedosov current in non-relativistic case is $\Phi = \frac{U}{3}$. For the vacuum limiting current, by the way, it is twice more, $2U/3$.

Approaches for control of cathode plasma.

There were many approaches on the way of solving the problem of REB expansion across magnetic field lines in the course of a microsecond REB pulse. Researchers in many laboratories applied cathodes of different materials and shapes, adjusted the geometry of magnetic and electric fields to that of the diode, etc. Here we consider only several ways intended to overcome the problem of the radial beam expansion.

The plasma transverse movement was scrutinized in the Institute of High-current electronics, Tomsk, USSR, at the end of 1970-th — beginning of 1980-th. Two mechanisms of plasma expansion were proposed (see, e.g., [1] and [6]). The first mechanism supposed plasma transverse velocity to be determined by a movement of neutrals ionization front: the neutrals may gain a velocity $\sim 10^6$ cm/s, intersect unimpeded the magnetic field lines and plasma frontier and then be ionized. According to the other mechanism, plasma may drift in crossed azimuthal electrical and longitudinal magnetic fields: presence of plasma filamentation (responsible for the presence of azimuthal fields) had been shown in experiments. Polarization of the azimuthally inhomogeneous plasma may cause development of instabilities, e.g., the centrifugal one.

At about the same time in Lebedev Physical Institute in Moscow another model was experimentally tested [7]. The model implies the polarization drift to be responsible for the cathode plasma movement. As it was indicated in the article, the velocity u of the polarization drift depends on the temporal behavior of the electric field E on the cathode surface: $u \sim \frac{\partial E}{\partial t}$.

Observations showed that cathode plasma radius remained stable at the front of diode voltage pulse and rose fast, $8 \cdot 10^5$ cm/s, in the course of the voltage pulse decay. As a result of the study it was recommended to use diode voltage pulses with flat or slightly rising plateau.

The radial expansion of the cathode plasma can be diminished by using magnetically-insulated coaxial diodes with converging magnetic field, i.e. the field increasing in the

downstream direction from the cathode [8, 9, 10]. In [8] the effect was explained as follows. First, in this inhomogeneous magnetic field, the plasma expands rapidly toward the cathode stalk under the action of the ponderomotive force $[\mathbf{j}_\theta \times \mathbf{B}_r]$ with \mathbf{j}_θ the azimuthal component of the current density in the cathode plasma and \mathbf{B}_r the radial component of the magnetic field. This force reduces the plasma density and, accordingly, the transverse velocity of the plasma. Second, such a converging magnetic field decreases the growth rate of the centrifugal instability.

Another possibility to affect the radial plasma velocity was seen on the way of variation of the cathode shape. Along with the sharp-edged cathodes, solid [6] and conical explosive-emission cathodes were used to suppress plasma expansion in the radial direction and, thus, to stabilize the transverse beam geometry. The proposal to apply a conical cathode for microsecond REB generation was made in [11], where a conical cathode was applied in a MID at an accelerator with 40 ns duration. The purpose was to generate a REB whose thickness should be high, actually it was 4 mm unlike 0.5 mm for sharp-edged cathodes. It was pointed there that "the described construction of MID allows not only to generate a REB stable to filamentation, but also to diminish significantly the beam current density on the cathode surface. This may be important for diminishing cathode plasma density and velocity at long-pulse, $\sim 1 \mu\text{s}$, installations".

The above two methods were often used together: in [12] the converging magnetic field lines were almost parallel to the surface of a conical surface of the cathode, in [9] the cathode surface also followed the curvature of the magnetic field lines. Nevertheless, the converging magnetic field allows to diminish the effect of plasma expansion but not to avoid it completely.

A possible way to prevent variations of the beam mean radius was implemented in [13, 14]. This method uses a rapid decrease of the magnetic field B at the emitting edge of cathode plasma with radius r_p in such a manner that this decrease should be significant in the course of the pulse. If the condition $B r_p^2 = \text{const}$ holds throughout the pulse, the electron-beam diameter does not increase. Measuring the radial profile of the beam current density showed that the influence of the radial cathode plasma expansion (and, accordingly, the beam radius variation) can be eliminated completely during ~ 700 ns.

One of the most effective ways to get rid of radial plasma expansion is to apply multipoint cathodes [15, 16]. In this case, their authors indicated, the expansion rate of the cathode plasma is determined not only by the magnetic field but also by the electric field. The

surface of the cathode plasma is almost steady when the emission current becomes equal to the saturation plasma current. In [15] the cathode was shaped as a sharp-angle cone with needles almost perpendicular to the guiding magnetic field. We do not share completely the explanation of multipoint cathode operation, but as it will be shown below, the sharp cathode edge perpendicular to magnetic field lines is the cornerstone of the cathode proposed in the present article.

The results described above are impressive, nevertheless, all these methods are very complicated in implementing, and each of the methods has its own significant drawbacks. To clone a diode with a multi-point cathode like [17] is a difficult task because "a very careful choice of electric and magnetic field shapes is needed". The multi-point cathode has a restriction in electron current density, and the method [18, 19] is hardly applicable with the pulse duration more than 1 μ s.

In this paper we propose a comparatively easy and cheap way to create a diode able to generate annular REBs with electron current densities of several kA/cm^2 and microsecond pulse duration.

Design of the diode.

Fig. 2 illustrates the design of the diode. Here and further the pictures assume azimuthal symmetry about z-axis. The shank supports the cathode inside a long drift tube where the magnetic field is strong (1 – 2 T) and homogeneous. Such a design forms the magnetically-insulated diode that allows to avoid the influence of longitudinal (along the magnetic field) plasma propagation. In the vacuum chamber where the shank is installed, the profile of the magnetic field lines may be different and determines the value of the return current from the cathode and the presence of electrons emitted from the shank.

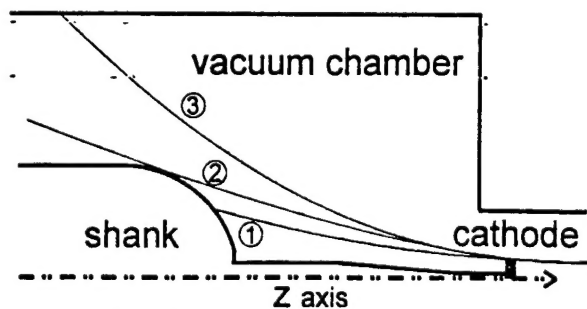


Fig. 2. Scheme of the diode.

With the cathode potential of 500 kV the electric field on the spherical surface of the shank exceeds a little the value of 50 kV/cm, and in the regime #1 (comparatively strong magnetic field near the shank) electrons emitted from its surface can penetrate into the drift

tube around the REB from the cathode. The return diode current is determined by the leakage of electron from the shank. In the regime #3 (magnetic field lines from the cathode are dispersed to the chamber walls) the return diode current comprises both electrons from the cathode and from the shank, increasing the total return current in comparison with the regime #1. The regime #2 is intermediate between the previous two ones: the return current from the cathode almost vanishes, but the electrons from the shank do not penetrate into the drift tube.

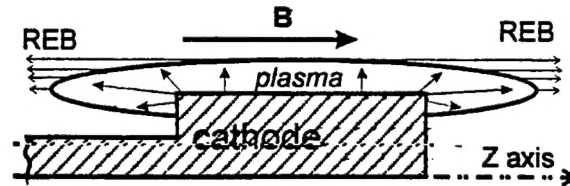


Fig. 3. Scheme of the radial plasma expansion.

The mechanism of electron beam expansion is illustrated in Fig. 3, briefly it is the following. Heating of the cathode surface at the outer radius (horizontal in Fig. 3) due to the electron emission initiates creation of dense plasma. At the right and left cathode edges plasma may move along the magnetic field lines, but for the centrally located particles, suffering collisions with identical "neighbors" from left and right, as well as from below, the only one way to expand remains: upwards to higher radii. In other words, the kinetic pressure pushes plasma perpendicularly to the outer cathode surface overcoming the magnetic field pressure. Plasma expands, and the radius of the REB increases as well. The amount of plasma depends, among other things, on the total current through the cathode, hence, if the return current from the cathode is significant (regime #3 in Fig. 2) the process of plasma creation has to be more intensive.

In order to avoid the described mechanism of plasma (and REB) expansion along the radius we propose to use cathodes with a sharp edge directed *perpendicularly* to the magnetic field lines (unlike the well-known cylindrical cathodes with the edge along the axis), as it is shown in Fig. 4. The cathode is supposed to be used in a magnetically-insulated diode.

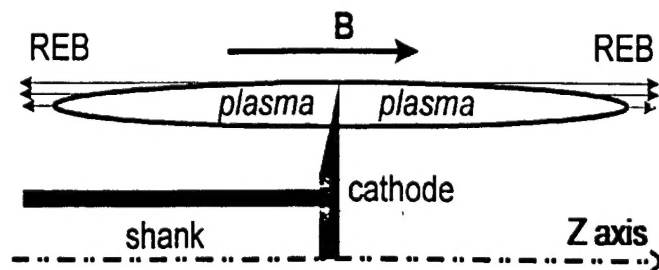


Fig. 4. Principle of operation of a cathode without radial plasma expansion.

Under the action of electron emission plasma appears on the cathode surface. Plasma covers not only the very edge, but also (and mostly) the adjacent areas, because the current density is finite, and in order to generate a certain total current an appropriate square of the surface must be engaged in the process. Unlike the scheme described in Fig. 3, the most part of plasma has a possibility to propagate along the magnetic field lines. The velocity of the longitudinal plasma propagation is at least one order more than its speed across the magnetic field ($\sim 10^5$ cm/s), the density (and, therefore, the kinetic pressure) diminishes, and plasma has no "strength" to overcome the magnetic field pressure and has to move along the axis. And the amount of plasma appeared on the outer border of the cathode is as little as sharp the edge is, and after even a minor expansion its density is absolutely insufficient to contribute distinctly to the total REB current.

In our long-term investigations since [20] we tested a lot of cathodes of different shapes and sizes, fabricated from different materials, but sharing the common property of a sharp edge at the external radius. In this paper we present one of the simplest and cheapest samples that nevertheless exhibits advantages of the proposed cathode shape. The cathode is made of stainless steel, its shape is shown in Fig. 4, the external radius is 1.4 cm, the angle at the edge about 5° , the edge thickness 0.2 mm. The cathode was immersed into a drift tube with the radius of 5.5 cm. Cathode voltage was about 500 kV, its waveform (denoted as U) is shown in Fig. 5. The homogeneous magnetic field in the drift tube was 1.8 T.

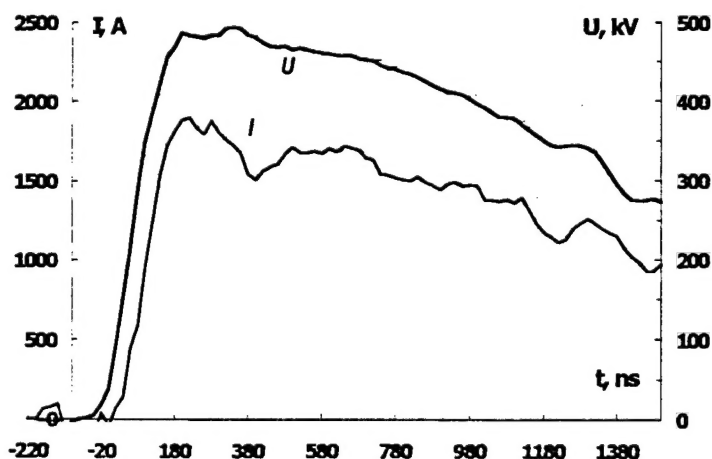


Fig. 5. Waveforms of cathode voltage U and REB current in the monitor I (normalized).

The construction of the monitor of the REB current density was described in [21]. Briefly, a part of an annular beam current passes through a radial slit (1 mm) and terminates on

several collectors, distributed over radius with the step of 1 mm. In the present work seven collectors were in use.

The waveform of the total current to the collectors is shown in Fig. 5 (denoted as I), its actual amplitude is multiplied by the ratio of the annular beam circumference length ($2\pi \cdot 14$ mm) to the monitor input slit thickness (1 mm). The shape of this waveform corresponds to that of voltage, the total beam current amplitude generated in the diode was 2 kA in accordance with Fedosov's formula: (4) and (12).

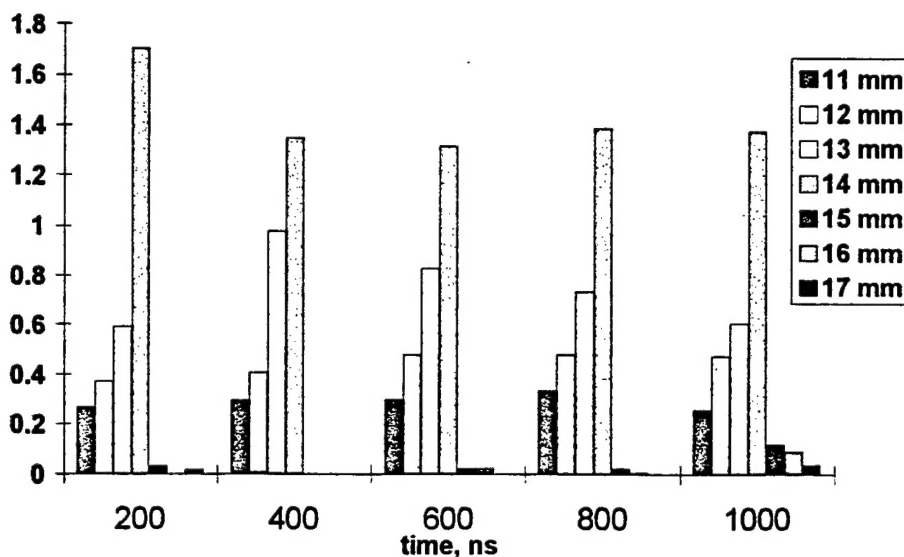


Fig. 6. Radial distributions of REB current density at different moments.

The result of measurements is shown in Fig. 6. The bar graphs present in arbitrary units the beam current density distributions 200 ns, 400 ns, etc. after the beginning of the REB propagation. Total current of the beam diminishes in the course of the pulse, as it is shown in Fig. 5, so the distributions are normalized. The profile of the magnetic field in the diode corresponds to the regime #2 in Fig. 2: the return current from the cathode is comparatively (to regime #3) small, and the electrons emitted from the shank should not penetrate into the drift tube.

In the course of all the pulse the beam current density remains distributed in approximately the same way: it has a sharp border at the external radius (that coincides with 14 mm of the cathode radius) and decreases toward the axis. The thickness of the annular beam at half-height is about 2 mm. The electrons emitted from the shank do not penetrate into